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Water quality impacts of stormwater discharges to Santa Monica Bay

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Abstract

Urban stormwater runoff is a major source of contaminants to southern California's coastal waters, yet little is known about the fate and effects of these discharges. A 3-year multidisciplinary project was conducted to investigate the dispersion of stormwater plumes in Santa Monica Bay and the resultant impacts on the water column and benthos. This paper describes the toxicity component of the study. Sea urchin fertilization toxicity tests were conducted on stormwater from the two largest discharges into the bay: Ballona Creek, which drains a highly urbanized watershed, and Malibu Creek, which receives runoff from a largely undeveloped watershed. Every sample of Ballona Creek stormwater tested was toxic (usually >5 toxic units), while Malibu Creek stormwater had a lower frequency and magnitude of toxicity (usually <4 toxic units). Surface water samples collected within the Ballona Creek stormwater discharge plume were always toxic whenever the concentration of stormwater in the plume exceeded 10%. The toxic portion of the Ballona Creek stormwater plume extended more than 4 km offshore on one occasion. Toxicity identification studies indicated that zinc was the primary cause of toxicity in both Ballona Creek stormwater and the discharge plume. No acute sediment toxicity (10-day amphipod survival) was present in the study area, although interstitial water toxicity was present at some stations located near the mouth of Ballona Creek. Differences in watershed characteristics likely were responsible for the greater toxicity of the Ballona Creek stormwater discharge plume. The Ballona Creek watershed contained a greater degree of urbanization (83% versus 12% for Malibu Creek) and the presence of a network of concrete flood control channels resulted in a stormwater plume containing elevated concentrations of

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toxics that received less initial dilution (compared to Malibu Creek) in the nearshore environment.

Keywords: Stormwater; Toxicity; Receiving water; Santa Monica Bay; Sea urchin

1. Introduction

Santa Monica Bay, like other coastal regions of southern California, receives contaminant inputs from a variety of sources. These inputs include the discharge of municipal wastewater (Raco-Rands & Steinberger, 2001) and industrial effluents (Raco-Rands, 1999), disposal of dredged material, atmospheric deposition (Stolzenbach et al., 2001), and urban runoff during wet and dry periods (Schiff, 1997). Improved point source control and advanced sewage treatment in southern California have greatly reduced the emissions of contaminants from sewage treatment plants and industrial discharges into the ocean over the last three decades. As a consequence, mass emissions from stormwater runoff now constitute a much larger portion of the constituent inputs to receiving waters and may represent the dominant source of some contaminants such as lead and zinc.

Southern California's coastal waters provide many beneficial uses, including recreation, aesthetic enjoyment, fishing, marine habitat, fish reproduction, industrial water supply, and navigation. Ocean-dependent activities contribute approximately $9 billion annually to the economies of coastal communities in southern California. Stormwater discharge has the potential to impair these beneficial uses through (1) contamination of recreational waters or seafood with disease-causing microbes, (2) aesthetic degradation from trash, odors, and reduced water clarity, and (3) ecosystem degradation from contaminants or other stormwater constituents.

The monitoring programs of various agencies collect information that is useful for assessing some beneficial use impairments related to stormwater, primarily those related to human health (Schiff, Morton, & Weisberg, 2001). While some monitoring programs measure the chemical composition and toxicity of stormwater sampled from channels and rivers, these programs do not assess the impacts of these discharges on the marine ecosystem. The size, persistence, and concentration of urban stormwater plumes in coastal areas have not been studied and the cause of adverse biological effects of stormwater discharges on water column and benthic marine life is unknown.

This study represents the first integrated effort to examine the physical, chemical, and toxic effects of stormwater discharges to marine life in southern California. The objectives of the toxicity portion of the study are to determine whether the toxic constituents in urban stormwater discharges have an adverse impact on coastal water quality, to characterize the toxicants of primary concern, and to determine whether sediment quality is affected by these discharges. This is the first research in southern California to examine the effects of dilution in the coastal environment on the magnitude and cause of stormwater toxicity. Results of concurrent research to examine dispersion and persistence of the stormwater plume and impacts on the benthic environment are reported in companion articles in the volume (Schiff & Bay, 2003, Washburn, McClure, Jones, & Bay, 2003).

2. Methods

2.1. Study design

This project used three approaches to examine the impact of urban stormwater discharge on Santa Monica Bay water quality: (1) comparative toxicity studies of stormwater runoff from two watersheds; (2) spatial studies of surface water and sediment toxicity in the bay; and (3) studies to identify the cause of toxicity in stormwater and surface water discharge plumes. The comparison of two watersheds provided an indication of the relative effect of urban vs. non-urban stormwater discharge on the bay. The Malibu Creek watershed is located in the northern portion of Santa Monica Bay and the second watershed, Ballona Creek, is located in the south-central portion of the bay (Fig. 1). Both watersheds are similar in size and, when combined, encompass over half of the entire Santa Monica Bay drainage area (Wong, Streckes, & Stenstrom, 1997). The Ballona Creek drainage basin is highly urbanized; 83% of the watershed is developed and comprised of predominantly residential land use. Almost the entire channel is concrete-lined. Conversely, 88% of the Malibu Creek watershed is open land and the channel is almost entirely earthen. These characteristics result in different flow and pollutant loading to the ocean from each watershed (LACDPW, 2000). Studies of the spatial patterns of toxicity (design element 2) included the analysis of surface water and sediment samples collected along gradients of stormwater plume concentration. This part of the study was intended to determine whether the discharge of stormwater from each creek was a substantial source of toxicity to the adjacent coastal environment. The third element

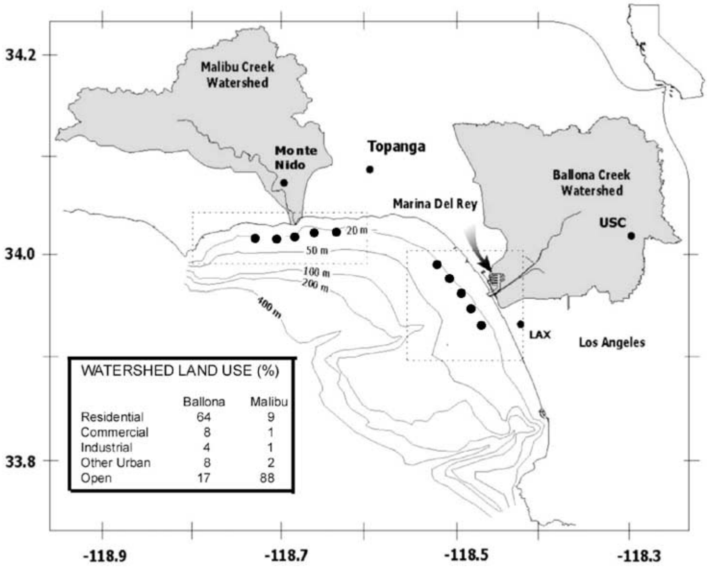

Fig. 1. Location of sediment and dry weather surface water sampling sites in Santa Monica Bay.

of the study (toxicant characterization) involved in-depth analysis of the chemical characteristics of toxicants in selected stormwater and plume samples. The purpose of these analyses was to further establish the link between stormwater discharge and receiving water impacts and to determine whether variations in receiving water characteristics (e.g. salinity, natural organic material) had an influence on the toxicants of concern.

2.2. Sampling

Samples of stormwater, surface water, and sediment were collected following storm events and during dry weather over three storm seasons, from January 1996 to January 1998. Surface water samples offshore of each creek were collected in conjunction with studies of plume mixing and dispersion (Washburn et al., 2003). Water samples associated with storm events were obtained with a submersible pump deployed amidships (at 10–30 cm depth) of the boat. The locations of these samples were determined by the distribution of the runoff plume and thus varied between storm events. Locations were usually selected according to the following criteria: one or two samples were obtained as close as practical to the creek mouth (representing the minimum salinity present in the area), one sample was obtained from a remote area (where salinity was at a background level), and 2–3 samples were collected from areas of intermediate salinity. Water samples were stored in glass bottles and placed on ice immediately after collection. Samples were stored in the dark at 5 °C. Most of the 139 stormwater or receiving water samples collected during the study were tested within 72 h of collection; five samples were stored for a longer period, 96–144 h. Variation in sample storage did not appear to affect the magnitude of toxicity.

Ballona Creek stormwater samples were obtained for 13 storm events that spanned the duration of the study, while samples of Malibu Creek stormwater were obtained from four events in 1996. Two methods were used to obtain stormwater samples: grab samples (1–4 per storm event) were obtained by lowering a plastic or stainless steel bucket from a bridge over each creek, and flow-weighted composites of selected storms at Ballona Creek were obtained from an automated sampling station operated by the Los Angeles County Department of Public Works. Sampling stations at each creek were located approximately 6 km upstream of the discharge point. Storage and handling of these samples was similar to the procedures described for receiving water.

Sediment samples were collected concurrently with sampling for sediment chemistry and benthic community composition on four occasions between February 1996 and July 1997 (Schiff & Bay, 2003). Samples were collected approximately one week following two storm events and also on two occasions during dry weather (July 1996 and July 1997). Five stations, each located at a depth of 25 m but at varying distances from the creek mouth, were sampled during each cruise (Fig. 1). An additional six stations, located in shallower water near the mouth of Ballona Creek, were sampled following one wet weather event to examine the occurrence of sediment toxicity in the immediate vicinity of the creek mouth. Sediment samples were obtained using a 0.1 m^2 modified Van Veen grab. Surficial sediments (top 2 cm) from undisturbed, representative grabs were collected and stored under refrigeration in plastic jars until analyzed for toxicity.

2.3. Toxicity analyses

2.3.1. Receiving water and stormwater

All samples of receiving water and stormwater were tested for toxicity using a sea urchin fertilization test (Chapman, Denton, & Lazorchak, 1995). The test consists of a 20-min exposure of sperm to the samples at 15 °C. Eggs are then added and given 20 min for fertilization to occur. The eggs are preserved and examined later with a microscope to assess the percent fertilized. Toxic effects are expressed as a reduction in fertilization percentage. Purple sea urchins (*Strongylocentrotus purpuratus*) used in the tests were collected from the intertidal in northern Santa Monica Bay. The tests were conducted in glass shell vials containing 10 ml of solution.

Water samples were not filtered or centrifuged to remove suspended solids before testing. Brine (prepared by the partial freezing of seawater) was added to samples with a salinity below 30 g/kg to adjust the salinity to 34 g/kg. Receiving water samples were tested at 100% concentration or the highest concentration possible after salinity adjustment. Four replicates of each sample were tested. Stormwater samples were adjusted for salinity and diluted with seawater to produce a concentration series usually consisting of 50, 25, 12, 6, and 3% stormwater. Three replicates of each concentration were tested. A negative control (0.45 μm and activated carbon filtered natural seawater from Redondo Beach) and brine control (distilled water containing 50% brine) were included in each test series for quality assurance purposes.

2.3.2. Interstitial water

The sea urchin fertilization test (described above) was used to measure the toxicity of interstitial water obtained from the sediment samples. Interstitial water was extracted from the sediment samples by centrifugation (30 min at 3000×g). Laboratory seawater was added to the samples to prepare test concentrations of 100 and 50%. Three or four replicates of each concentration were tested for toxicity.

2.3.3. Sediment

The toxicity of the bulk sediment samples was assessed by measuring the survival of amphipods following a 10-day exposure period. Test methods followed standard guidelines (ASTM, 1991). A 1-l sediment sample was removed from storage and homogenized by hand. A 2-cm layer of sediment was then added to five replicate one-quart glass canning jars for each station. Approximately 750 ml of lab seawater, adjusted to a salinity of 30 g/kg, was added to each jar. The jars were fitted with aeration tubes and allowed to equilibrate overnight before addition of the amphipods. Twenty amphipods (*Rhepoxynius abronius*) were added to each jar. The test animals were collected from Puget Sound (Washington). A sample of collection site sediment was also included in the test, as a negative control. The test was conducted at 15 °C, under constant illumination. Surviving animals were removed from the sediment at the end of the exposure by sieving and counted to determine the percent survival.

2.4. Toxicant identification

Toxicity identification evaluation (TIE) studies were conducted on selected samples of Ballona Creek stormwater and surface water samples from the discharge plume offshore Ballona Creek. Each sample was treated using modified EPA Phase I TIE methods (Burgess, Ho, & Morrison, 1996) in order to characterize the toxicants present. A portion of each water sample was adjusted to normal seawater salinity before applying the following TIE treatments: addition of 15 or 30 mg/l EDTA to complex cationic trace metals, addition of 25 mg/l sodium thiosulfate to reduce oxidants, or filtration through a 1.0 μm glass fiber filter to remove particulates. A portion of the filtered sample was also passed through a C_{18} solid phase extraction column to remove nonpolar organics. The effectiveness of each TIE treatment was assessed by measuring the change in toxicity of the treated sample relative to an untreated sample (baseline toxicity). Each treatment was tested at two concentrations: the maximum possible after salinity adjustment and 25% of that concentration. Blanks, consisting of laboratory seawater treated with each TIE procedure were also analyzed to verify that the treatments did not produce artifactual results.

2.5. Data analysis

The statistical significance of changes in sea urchin fertilization percentage among dilutions of the water samples was tested using Dunnet's multiple comparison procedure (alpha = 0.05) following arcsine tranformation of the data. The magnitude of toxicity of the stormwater samples was described using three statistics, which were calculated from the dose response data from the dilution series. The NOEC (no observed effect concentration) is the highest concentration of sample that did not produce a significant adverse response on fertilization. The EC50 (median effective concentration) represents the concentration of sample calculated to produce a 50% reduction in fertilization. This statistic was calculated using probit analysis. The toxic units of each sample was calculated as 100/EC50.

3. Results

3.1. Stormwater toxicity

Toxicity was usually detected in stormwater samples from both watersheds (Table 1). Every sample from Ballona Creek was toxic, with NOECs ranging from <3 to 25%. Toxicity was also detected in three of four samples of Malibu Creek stormwater, but at a lower level relative to Ballona Creek.(NOEC usually ⩾25%).

Analysis of multiple grab samples indicates substantial variability among storms, with evidence of a seasonal pattern. The first storm of the year that generated runoff in Ballona Creek was sampled on two occasions (30 October 1996 and 25 September 1997), stormwater produced by these storms was more than three times as toxic (toxic units) as subsequent storms, regardless of the amount of rainfall (Table 1).

3.2. Receiving water toxicity

Toxicity was present in surface water samples collected within the discharge plume near the mouth of Ballona Creek during virtually every sampling event. Spatial plots of the results showed a similar pattern for each event: greater toxicity was usually present in water samples collected nearest the mouth of Ballona Creek and samples collected outside the boundary of the plume (as determined from salinity measurements) were nontoxic (Fig. 2). The offshore extent of surface water toxicity varied greatly among storms, however. For example, toxicity extended at least 4 km offshore during the 21 February 1996 cruise, which followed a relatively large storm

Table 1
Summary of sea urchin fertilization toxicity test results for Ballona Creek and Malibu Creek stormwater samples

Creek	Date	Sample type[a]	Antecedent days	Rainfall (in.)	NOEC (%)[b]	EC50 (%)[c]	Toxic units
Ballona	1/16/96	Grab	23	0.2	6	11	9
	1/21/96	Grab	1	0.6	25	> 50	< 2
	1/31/96	Grab	3	2.2	6	15	7
	2/19–22/96	Grab	15	4.0	12	18	6
	10/30/96	Grab	196	1.3	< 3	< 3	> 33
	11/21/96	Grab	22	1.8	3–12	10–11	10–9
	12/09/96	Composite	4	3.1	6	21	5
	1/12/97	Composite	9	2.2	25	> 50	< 2
	1/23/97	Composite	1	2.4	12	36	3
	9/25/97	Grab	227	0.4	3	4	25
	1/19/98	Grab	3	0.16	3	12	8
	2/23/98	Composite	1	4.2	12	30	3
	3/25/98	Composite	10	2.1	6	11	9
Malibu	1/31/96	Grab	38	0.6	3–25	5–35	20–3
	2/1/96	Grab	0	0	12–25	28	4
	2/19–22/96	Grab	19	1.4	≥ 50	32- > 50	3- < 2
	10/29–30/96	Grab	229	1.5	25	> 50	< 2

[a] Grab samples (1–4 per event) were collected by hand at various times during the storm event, a range is given for the toxicity response data when the results for multiple grabs differed substantially. Composite samples were collected by an automated sampler and flow weighted.

[b] Highest concentration that does not produce statistically significant reduction in fertilization. Values preceded by "≥" were not toxic at the highest concentration tested (25 or 50%).

[c] Concentration producing a 50% reduction in fertilization. Values preceded by ">" produced less than a 50% effect at the highest concentration tested (25 or 50%).

event (4.0 in rainfall), but toxicity was restricted to a relatively small region ($\leqslant 1$ km offshore of Ballona Creek) during the 5 March sampling cruise (Fig. 2). The samples showing toxicity within the plume contained $>10\%$ runoff, calculated from the salinity of the test samples. An insufficient number of samples were collected during the cruise to examine the longshore extent of the toxic portion of the plume.

Toxicity was rarely detected in water samples collected near the mouth of Malibu Creek during some of the same storm events. No toxicity was detected in two sets of samples collected offshore of Malibu Creek during cruises in February and March 1996 (data not shown). Toxicity was not expected in these Malibu samples, since relatively small runoff plumes were present and all toxicity samples contained less than 2% runoff.

Surface water samples collected offshore of Ballona Creek during the 10–11 December 1996 storm event were toxic whenever the samples contained $\geqslant 7\%$ stormwater. A spatial plot of the data shows that toxicity extended about 1.2 km offshore and at least 1 km upcoast from the mouth of Ballona Creek (Fig. 2). The surface water sampling offshore of Malibu Creek on 11 December detected a larger discharge plume compared to the first year of study and several water samples were obtained during this event that contained $\geqslant 10\%$ runoff; No toxicity was detected in

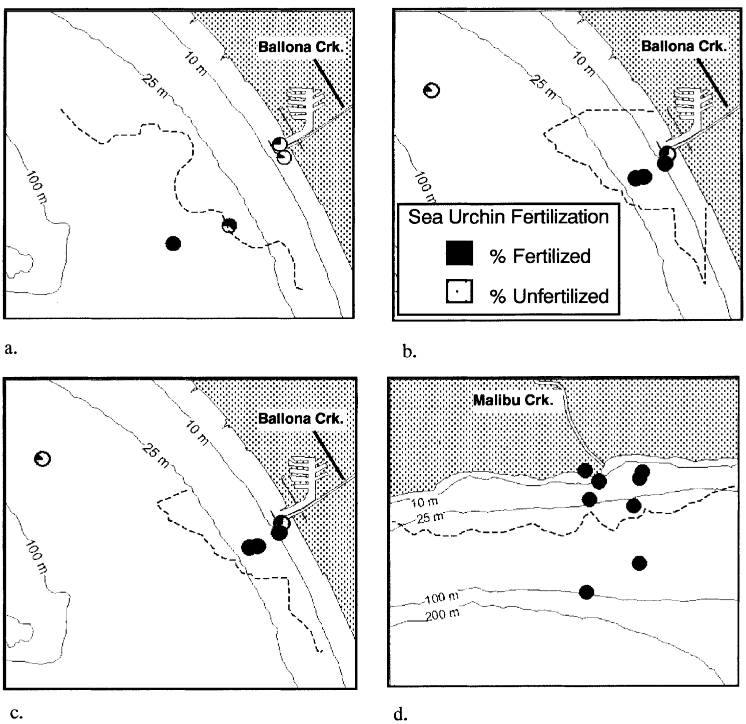

Fig. 2. Toxicity test results for surface water samples collected on 21 February 1996 (a), 5 March 1996 (b), 10 December 1996 (c), and 11 December 1996 (d). Dashed line indicates the outer margin of the discharge plume.

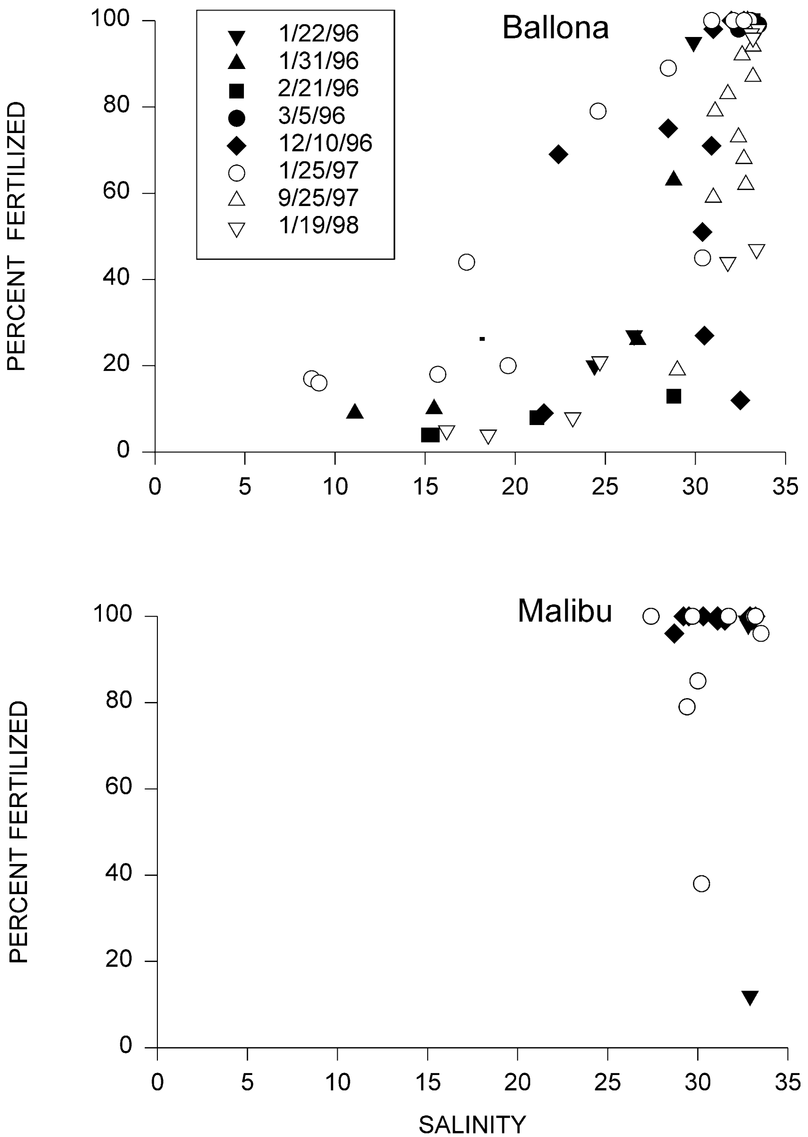

Fig. 3. Relationship between sea urchin toxicity and salinity (at time of collection) of surface water samples. The salinity of all samples was adjusted to 34 g/kg prior to testing.

these samples, however (Fig. 2). Surface water toxicity was detected offshore Malibu Creek in samples collected during subsequent cruises, but the spatial pattern and magnitude of toxicity in these samples showed a poor correspondence with the magnitude and location of the discharge plume. The greatest toxicity offshore of Malibu was measured in samples collected outside of the plume, while samples from within the plume that contained 10–15% runoff showed an inconsistent pattern of

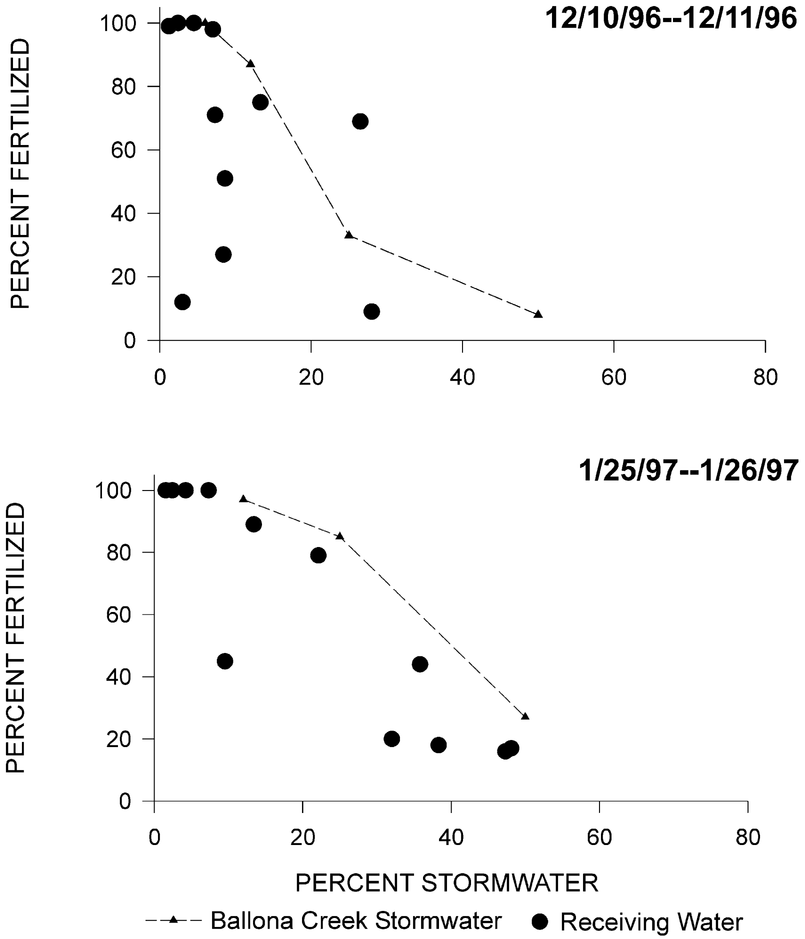

Fig. 4. Comparison of sea urchin fertilization test results for Ballona Creek stormwater and nearby surface water.

toxicity. A strong red tide was present off the coast of Malibu at the time of sampling and may have influenced water quality.

Surface water samples from offshore of Ballona Creek were obtained following eight storm events during the course of the study. In every case, toxicity was observed in samples having a salinity of $\leqslant 30$ mg/kg (Fig. 3), which corresponded to the presence of at least 10% stormwater in the sample. While the magnitude of toxicity associated with a particular salinity varied among sampling events, a pattern of greater toxicity in those samples with the lowest salinity was always observed. Surface water samples collected offshore of Malibu Creek following three storm events did not display a similar association between toxicity and salinity (Fig. 3). Though toxicity was observed on two occasions, other samples containing the same salinity (and therefore the same concentration of stormwater) did not contain any toxicity.

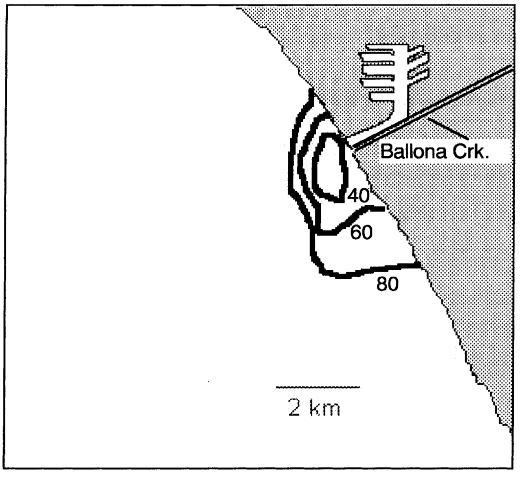

Fig. 5. Map of predicted surface layer toxicity to sea urchins resulting from stormwater discharge from Ballona Creek on 10 December 1996. The contour lines indicate the predicted percentage fertilization.

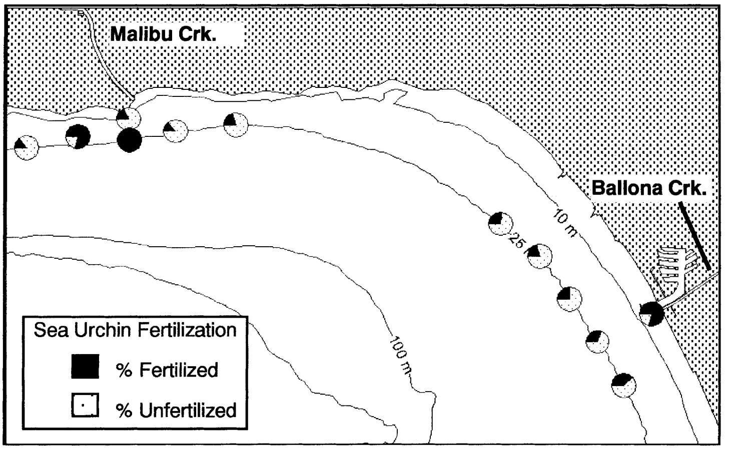

Fig. 6. Toxicity test results for dry season surface water collected in July 1997.

The variation in toxicity with varying salinity in the samples collected offshore of Ballona Creek suggests that the magnitude of toxicity was related to the concentration of stormwater present. This dose response relationship was very similar to that measured for samples of Ballona Creek stormwater collected during the same storm event (Fig. 4). In most cases where concurrent samples of stormwater and surface water were analyzed, the toxicity of the surface water was similar or greater than that predicted by the dose response curve of the stormwater sample.

The toxicity and concentration data from the test of the 9 December 1996 Ballona Creek stormwater sample were fit to a logistic regression in order to obtain a function that predicted the toxicity corresponding to various stormwater concentrations.

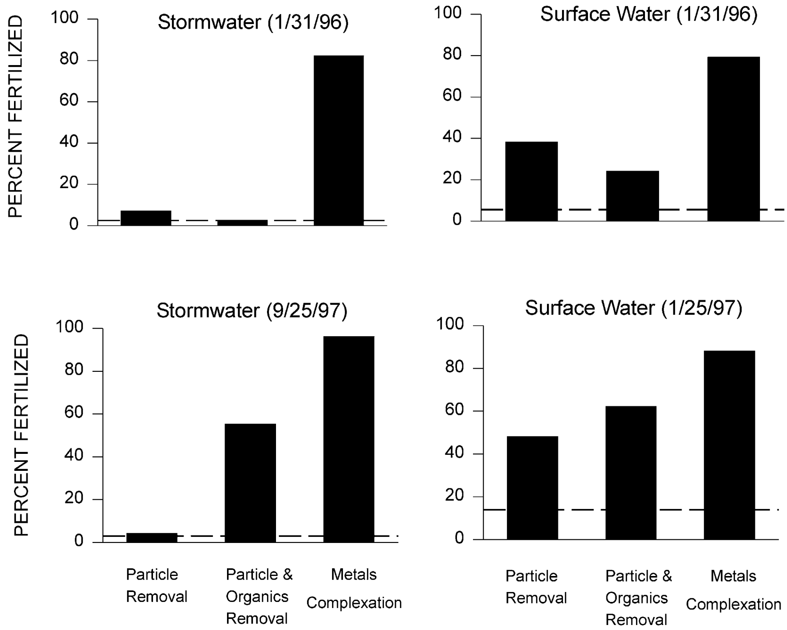

Fig. 7. Toxicity identification evaluation results for selected Ballona Creek stormwater and surface water samples. The dashed line indicates the toxicity test response of the baseline (untreated) sample.

This function was then combined with surface water salinity data from the 10 December plume mapping to produce a map of surface water toxicity offshore of Ballona Creek (Fig. 5). The area of predicted surface water toxicity extended approximately 1.5 km offshore and approximately 2 km alongshore, with the greatest magnitude of toxicity centered directly offshore of Ballona Creek.

Surface water samples collected during two surveys conducted in the dry season also contained varying amounts of toxicity (Fig. 6). Toxicity was present in 53% of the dry weather water samples collected during July 1996 and July 1997. The location of these toxic samples varied between surveys and did not show a consistent relationship with the location of Ballona Creek or Malibu Creek.

3.3. Toxicant identication

The application of Phase I TIE treatments to selected Ballona Creek stormwater samples produced a similar effect on toxicity in each case. Addition of EDTA, a strong ligand of trace metals, always produced a complete elimination of toxicity (Fig. 7). Treatment of the sample with solid phase extraction to remove nonpolar organics was occasionally effective, this treatment rarely eliminated all of the toxicity, however. Treatments to remove particles (filtration) or neutralize oxidants (thiosulfate) were ineffective. The pattern of response was similar in all six stormwater samples analyzed over the course of three years.

Application of the TIE treatments to surface water samples collected offshore of Ballona Creek produced similar but more variable results (Fig. 7). Addition of EDTA also consistently eliminated toxicity in all nine surface water samples, for which sufficient toxicity was present to conduct the TIE analysis. The filtration and solid phase extraction treatments were also usually partially effective in these TIEs. Much of the reduction in toxicity shown for the solid phase extraction treatment was actually due to the filtration step, which was performed on the samples prior to extraction.

Since the TIE results implicated metals as the likely toxicants, the concentrations of trace metals in stormwater were examined. Additional samples of Ballona Creek stormwater were analyzed for trace metals during 1996–1998 by the Los Angeles Department of Public Works as part of their municipal stormwater monitoring program (LACDPW, 2000). These analyses showed that Ballona Creek stormwater contained detectable total recoverable concentrations of chromium, copper, iron, lead, manganese, mercury, nickel, selenium, zinc. Of these metals, only barium, copper, nickel, and zinc were reported as detectable in the dissolved phase (Table 2), which is the fraction expected to cause toxicity to organisms exposed from the water. Dissolved zinc was present at the highest concentration, with a mean value of 66 μg/l. This concentration is approximately twice the fertilization EC50 and eight times the NOEC measured for zinc in laboratory experiments (Table 2). None of the other stormwater metals were present at average concentrations likely to produce detectable toxicity, especially after dilution upon discharge. Average reported dissolved copper concentrations were similar to the fertilization NOEC for this metal. Because of the variability in stormwater metal concentration between storms, it is likely that some samples contained toxic concentrations of copper.

Table 2
Comparison of measured dissolved metal concentrations in Ballona Creek stormwater with toxicity measured using the sea urchin fertilization test. All data are expressed as μg/L

	Toxicity[a]		Stormwater concentration[b]	
Metal	NOEC	EC50	Mean	S.D.
Arsenic			<5	
Barium	>1000	>1000	39	25
Cadmium	3700	11,500	<1	
Chromium	>100,000	>100,000	<5	
Copper	17	30	13	14
Lead	>4000	>4000	<5	
Manganese	>40,000	>40,000	<100	
Mercury			<1	
Nickel			6	4
Silver			<1	
Zinc	8	29	66	88

[a] Toxicity data from experiments conducted at SCCWRP using seawater spiked with individual trace metals.

[b] Mean and standard deviation of approximately 35 composite samples analyzed during 1996–2000 (LACDPW 2000).

3.4. Sediment toxicity

Sediments from the two dry weather sampling events (July 1996 and July 1997) and two post-storm events (February 1996 and February 1997) were evaluated for sediment toxicity. No toxicity was detected in any of the post-storm samples using the 10-day amphipod survival test (Table 3). Amphipod survival was $\geqslant$83% in all samples, which is within the range characteristic of nontoxic sediments. Of the dry weather samples, reduced survival was observed following exposure to sediment from Malibu station E2, located 4 km downcoast of the creek mouth (Table 3). Average survival for this station was low (57%), but highly variable, with >90% survival in three replicate test chambers and no survival in the remaining two chambers. These highly variable results may have been due to noncontaminant related factors, such as predation by resident organisms or poor water quality in some of the test replicates.

Tests for interstitial water toxicity were conducted during both storm events and the July 1996 sediment surveys. No reduction in sea urchin fertilization was measured for the dry weather samples. Analysis of the February 1997 samples identified toxic interstitial water at both the Ballona Creek and Malibu Creek study sites, however. Toxicity was most frequent and of greater magnitude offshore Ballona Creek (Fig. 8). The strongest response offshore of Ballona Creek was present in stations located along a shallow water transect extending from the creek mouth (and Marina del Rey) and in sediment from stations located within 2 km (upcoast or downcoast) of Ballona Creek (Fig. 8). Fine-scale patchiness in toxicity was also present, as shown by markedly different test results for two adjacent stations located just offshore of the Marina del Rey breakwater. There was no relationship between interstitial water toxicity and water quality characteristics (ammonia concentration, pH, or dissolved oxygen concentration).

Interstitial water from a reference area offshore of Dana Point in Orange County (R52-60) also was tested with the February 1997 samples. Exposure to 100% Dana Point interstitial water produced 55% fertilization. This fertilization value was

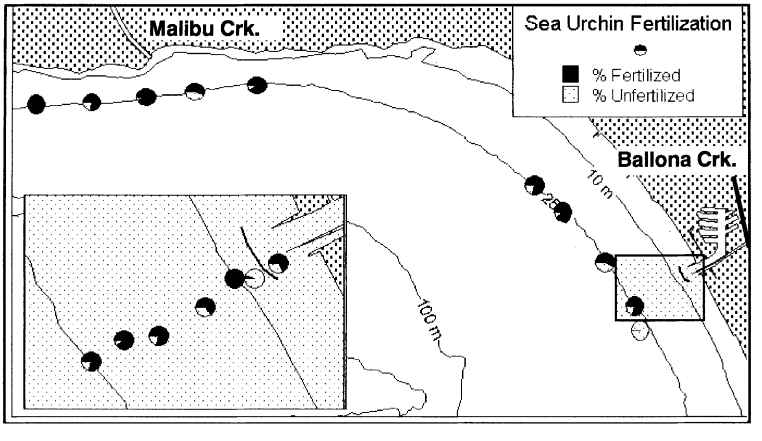

Fig. 8. Interstitial water toxicity test results for sediment samples collected in February 1997 following a storm event.

Table 3
Summary of sea urchin fertilization test (interstitial water) and amphipod survival test (bulk sediment) results for samples collected in dry and wet weather (July and February, respectively). Distance refers to the up coast (positive values) or down coast (negative values) direction, relative to the creek mouth

				2/28/96		7/30/96		2/5-6/97		7/31/97
Creek	Station	Distance from creek (km)	Depth (m)	Fertilization (%)	Survival (%)	Fertilization (%)	Survival (%)	Fertilization (%)	Survival (%)	Survival (%)
Malibu	E2	−4	25	98	93	97	57	89	83	98
	A2	−2	25	99	91	97	89	58	96	94
	B2	0	25	95	90	98	92	92	90	96
	C2	2	25	99	93	98	94	76	92	95
	D2	4	25	99	89	96	94	100	89	97
Ballona	A2	−2	25	98	93	97	96	0	92	97
	B2	0	25	98	95	97	95	78	89	95
	C2	2	25	95	89	100	98	58	83	95
	D2	4	25	96	97	97	99	88	95	95
	E2	6	25	42	98	94	87	78	93	94
	0I	0	3					67	84	
	0A	0	10					5	95	
	0B	0	11					99	98	
	0C	0	14					64	91	
	0D	0	18					79	92	
	0E	0	22					89	95	

similar to that recorded for most of the samples from the Ballona Creek study site (Fig. 8). Only two stations contained interstitial water that produced a greater toxic effect than interstitial water from the reference site.

4. Discussion

The results of this study provide four lines of evidence that the discharge of stormwater from Ballona Creek is a source of impairment to water quality in Santa Monica Bay. First, Ballona Creek stormwater was found to be consistently toxic to marine life, as demonstrated by the sea urchin fertilization test. These tests were conducted on salinity-adjusted samples of stormwater and show that toxicity was due to chemical constituents, not salinity effects.

Measurements of toxicity within the surface layer of the discharge plume provide the second line of evidence for impaired water quality. These studies showed that the initial dilution of Ballona Creek stormwater upon discharge was not sufficient to reduce the toxicants to nontoxic concentrations. The spatial pattern of surface water toxicity indicated the greatest toxicity near the mouth of Ballona Creek, further implicating this creek as the source of toxicity.

The magnitude of toxicity in Ballona Creek stormwater and the discharge plume were similar, providing a third line of evidence linking receiving water impacts to stormwater discharge. The change in surface water toxicity in proportion to the concentration of freshwater present was similar to that predicted from dilutions of Ballona Creek stormwater. This finding is consistent with Ballona Creek stormwater being the principal source of toxicity to the surface water. The similarity of dose responses between stormwater and surface water samples also validates the use of laboratory tests of stormwater toxicity for estimating receiving water impacts.

The similarity in toxicant characterization results between stormwater and surface water samples provides the final evidence associating Ballona Creek discharge with water quality impairment. TIEs of both types of samples indicated trace metals were the principal toxicants present. These results are consistent with Ballona Creek stormwater being the primary source of wet weather surface water toxicity in the nearby coastal zone.

The discharge of urban stormwater is likely to result in surface water toxicity in other southern California coastal locations. Toxic stormwater plumes were found to result from stormwater discharge into San Diego Bay (Schiff, Bay, & Diehl, 2003) and Newport Bay (Lee, Taylor, & Neiter, 1999). Other studies of receiving water impacts have not been conducted in southern California, but toxicity has been detected in several other rivers or creeks that discharge into coastal waters, suggesting the potential for surface water impacts. Studies in additional locations are needed to gauge the extent of stormwater impacts on southern California coastal water quality.

Though stormwater discharge has been observed to produce toxic effects over several km^2 of Santa Monica Bay (Fig. 5), these effects are likely to be relatively short-lived; wind, waves, and other mixing processes tend to disperse the most concentrated portion of the plume within several days (Washburn et al., 2003). The toxic effects of contaminated sediments discharged in stormwater have a greater potential to create long-term impacts, if these sediments accumulate to harmful levels on the seafloor. The sediment toxicity tests conducted during this study detected only sublethal levels of toxicity in interstitial water. No acute impacts on amphipod survival that could be associated with stormwater discharge were found, which is consistent with the analyses of benthic community structure conducted at the same time (Schiff & Bay, 2003). Sublethal levels of toxicity were detected in interstitial water from sediment located very near the mouth of Ballona Creek, but in most cases this toxicity was similar to that measured at the reference site. Interstitial water toxicity at the mouth of Ballona Creek also was detected by Noblet, Bay, Stenstrom, and Suffet (2001) in a separate study. These results indicate that the stormwater-related toxic impacts to sediments are restricted to a relatively small area in the immediate vicinity of Ballona Creek.

The extent of stormwater impacts to the sediment environment is dependent upon the fate of the stormwater particles. At Ballona Creek, most of the stormwater particle load was dispersed throughout Santa Monica Bay by wave action and shoreline currents. Sediment impacts may be more severe at other locations, where greater stormwater particle deposition occurs. For example, extensive deposition of stormwater particles occurs at the mouth of the Los Angeles River, which discharges into Long Beach harbor (a nondispersive environment). Recent studies have shown that sediments near the mouth of the Los Angeles River contain higher levels of toxicity that most other areas in Los Angeles County (Bay et al., 2000).

The lack of stormwater-related toxicity in the coastal zone offshore of Malibu Creek illustrates the impact of watershed characteristics in addition to differences in the chemical composition of the stormwater. Stormwater discharge from Malibu Creek produced plumes that were less concentrated and distinct compared to discharges from Ballona Creek (Washburn et al., 2003). These differences are likely due to a greater degree of perviousness and the more natural drainage/lagoon system present in the Malibu Creek watershed. The extensive urbanization of the Ballona Creek watershed, accompanied by the concrete-lined flood channel system, favors the generation of more concentrated discharge plumes, which enhances the potential for toxic impacts in the water column.

Evidence of non-stormwater sources of surface water toxicity were also found during this study. The presence of surface water toxicity during dry weather and greater than expected toxicity in some wet weather surface water samples indicates that there may be other significant sources of impaired water quality in Santa Monica Bay. The tidal flushing of nearby Marina del Rey (the largest recreational boat harbor in California) may be a year-round source of toxic surface water near Ballona Creek. Limited sampling conducted during this project detected toxicity in water samples collected from the marina. Further studies are needed to understand the frequency, spatial extent, and cause of toxicity from this and other sources.

The toxicity identification studies conducted during this study identified trace metals, especially zinc, as a primary toxicant of concern. Similar TIE results using the sea urchin fertilization test have been obtained for other watersheds in southern California. Zinc was also identified as a primary toxicant in studies of stormwater toxicity from Chollas Creek in San Diego (Schiff et al., 2003). Preliminary TIEs also have implicated zinc as an important toxicant in stormwater discharges from the city of Long Beach (Kinnetic Laboratories and SCCWRP, 2001).

There may be other toxicants of concern in stormwater discharges to Santa Monica Bay. Studies of other watershed throughout California have frequently identified organophosphorus pesticides (i.e. diazinon and chlorpyrifos) as the cause of stormwater toxicity (de Vlaming et al., 2000). Most studies that have identified pesticides as a cause of stormwater toxicity have used fresh water crustaceans, such as the water flea *Ceriodaphnia dubia*, as the test organism. Toxicity tests using crustaceans are much more sensitive than the sea urchin fertilization test to these pesticides. Thus, tests using several species are needed to provide a complete assessment of the toxicants of concern in stormwater discharges.

This study has demonstrated the value of using a variety of toxicity test methods to evaluate the potential for biological impacts from stormwater discharge. Laboratory studies of stormwater samples provide essential information to characterize and rank the toxic potential of stormwater discharges. But toxicity analyses of field samples in combination with physical measurements of the plume are also needed to determine extent and persistence of receiving water impacts.

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